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HIGGS QUARK COUPLINGS IN SUSY WITH CP AND FLAVOR VIOLATIONS

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In minimal supersymmetric model with a light Higgs sector, explicit CP violation and most general flavor mixings in the sfermion sector, integration of the superpartners out of the spectrum induces potentially large contributions to the Yukawa couplings of light quarks via those of the heavier ones. These corrections can be sizeable even for moderate values of $\tan\beta$, and remain nonvanishing even if all superpartners decouple. Then Higgs boson couplings to light quarks assume spectacular enhancements; in particular, couplings to down and strange quarks become degenerate with that to the bottom quark. There arise strikingly non-standard effects that can show up in both Higgs boson searches and FCNC observables.

The primary goal of the existing and planned colliders and of the meson factories is to test the standard model (SM) and determine possible 'new physics' effects on its least understood sectors: breakdown of CP, flavor and gauge symmetries. In the standard picture, both CP and flavor violations are restricted to arise from CKM matrix, and the gauge symmetry breaking is accomplished by introducing the Higgs field. However, the Higgs sector is badly behaved at quantum level; its stabilization against quadratic divergences requires supersymmetry (SUSY) or some other extension of the standard model (SM). The soft breaking sector of the MSSM accommodates novel sources for CP and flavor violations [1,2]. The Yukawa couplings, which are central to Higgs searches at the LHC, differ from all other couplings in the lagrangian in one aspect: the radiative corrections from sparticle loops depend only on the ratio of the soft masses and hence they do not decouple even if the SUSY breaking scale lies far above the weak scale. In this sense, non-standard hierarchy and texture of Higgs-quark couplings, once

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confirmed experimentally, might provide direct access to sparticles irrespective of how heavy they might be. This talk is intended to summarize the results of recent work [3] which discusses the radiative corrections to Yukawa couplings from sparticle loops and their impact on FCNC observables and Higgs phenomenology.

The soft breaking sector mixes sfermions of different flavor via the off–diagonal entries of the sfermion mass–squared matrices. The LR and RL blocks are generated after the electroweak breaking with the maximal size $O(m_t M_{SUSY})$, and their flavor mixing potential is dictated by the Yukawa couplings $\mathbf{Y}_{u,d}$ and by the trilinear coupling matrices $\mathbf{Y}^A_{u,d}$ with $\left(\mathbf{Y}^A_{u,d}\right)_{ij} = \left(\mathbf{Y}_{u,d}\right)_{ij}\left(A_{u,d}\right)_{ij}$ where $A_{u,d}$ are not necessarily unitary so that even their diagonal entries contribute to CP–violating observables. The flavor mixings in LL and RR sectors, however, are insensitive to electroweak breaking; they are of pure SUSY origin. Clearly, CP violation in LL and RR sectors is restricted to the flavor-violating entries due to hermiticity.

The effective theory below the SUSY breaking scale M_{SUSY} consists of a modified Higgs sector; in particular, the tree level Yukawa couplings receive important corrections from sparticle loops. For instance, the d quark Yukawa coupling relates to the physical Yukawas via

$$h_d = \frac{g_2 \overline{m_d}}{\sqrt{2} M_W}\ \frac{\tan\beta}{1+\epsilon_\beta}\ \left[1 - \frac{\epsilon_\beta}{1+\epsilon_\beta}\ \left\{\frac{\overline{m_s}}{\overline{m_d}}\left(\delta^d_{12}\right)_{LR} + \frac{\overline{m_b}}{\overline{m_d}}\left(\delta^d_{13}\right)_{LR}\right\}\right] \quad (1)$$

where $\overline{m_i}$ are the running quark masses at M_{SUSY}, $\epsilon_\beta = \epsilon\tan\beta$, $\epsilon = (\alpha_s/3\pi)e^{-i(\theta_\mu+\theta_g)}$, and

$$\left(\delta^d_{ij}\right)_{LR} = \frac{1}{6}\ \left(\delta^d_{ij}\right)_{RR}\left(\delta^d_{ji}\right)_{LL} \quad (2)$$

with the SUSY CP–odd phases defined as $\theta_g = \mathrm{Arg}[M_g]$, $\theta_\mu = \mathrm{Arg}[\mu]$, $\theta^d_{ij} = \mathrm{Arg}[(A_d)_{ij}$ so on. The mass insertions $\left(\delta^{d,u}_{ij}\right)_{RR,LL}$ are defined as the ratio of (i,j)–th entry of $\left(M^2_{D,U}\right)_{RR,LL}$ to the mean of the diagonal entries. The structure in (1) repeats for other quark flavors as well. In contrast to the minimal flavor violation (MFV) scheme, the Yukawa couplings acquire large corrections from those of the heavier ones as suggested by the terms in square bracket. Indeed, the radiative corrections to $h_d/\overline{h_d}$, $h_s/\overline{h_s}$, $h_u/\overline{h_u}$ and $h_c/\overline{h_c}$ involve, respectively, the large factors $\overline{m_b}/\overline{m_d} \sim (\tan\beta)^2_{max}$, $\overline{m_b}/\overline{m_s} \sim (\tan\beta)_{max}$, $\overline{m_t}/\overline{m_u} \sim (\tan\beta)^3_{max}$, and $\overline{m_t}/\overline{m_c} \sim (\tan\beta)^2_{max}$ with $(\tan\beta)_{max} \lesssim \overline{m_t}/\overline{m_b}$. Unlike the light quarks, the top and bottom Yukawas remain stuck to their MFV values to a good approximation. Therefore, the SUSY flavor violation sources mainly influence the light sector whereby

modifying several processes they participate. These corrections are important even at low $\tan\beta$. As an example, consider $\left(\delta^d_{13}\right)_{LR} \sim 10^{-2}$ for which $h_d/h_d^{MFV} \simeq 0.02(2.11), -2.3(6.6), -4.6(17.7)$ for $\tan\beta = 5, 20, 40$ at $\theta_\mu + \theta_g \rightsquigarrow 0(\pi)$. Note that the Yukawas are enhanced especially for $\theta_\mu + \theta_g \rightsquigarrow \pi$ which is the point preferred by Yukawa–unified models such as SO(10). In general, as $\tan\beta \to (\tan\beta)_{max}$ the Yukawa couplings of down and strange quarks become amproximately degenerate with the bottom Yukawa for $\left(\delta^d_{13,23}\right)_{LR} \sim 0.1$ and $\theta_\mu + \theta_g \rightsquigarrow \pi$. There is no $\tan\beta$ enhancement for up quark sector but still the large ratio $\overline{m_t}/\overline{m_u}$ sizeably folds h_u compared to its SM value: $h_u \simeq 0.6\ e^{i(\theta^u_{11} - \theta_g)}\ \overline{h_c}$ with $(\delta^u_{13})_{LR} \sim 0.1$.

The SUSY flavor violation influences the Higgs-quark interactions by (i) modifying $H^a \overline{q} q$ couplings via sizeable changes in Yukawa couplings, and by (ii) inducing large flavor changing couplings $H^a \overline{q} q'$:

$$
\begin{aligned}
&\frac{\overline{h_{d^i}}^{SM}}{\sqrt{2}} \left[\frac{h^i_d}{\overline{\overline{h^i_d}}}\ \tan\beta\ C^d_a + \left(\frac{h^i_d}{\overline{\overline{h^i_d}}} - 1 \right) \left(e^{i(\theta^d_{ii} + \theta_\mu)}\ C^d_a - C^{u\star}_a \right) \right]\ \overline{d^i_R}\ d^i_L\ H_a \\
&+ \frac{\overline{h_{d^i}}^{SM}}{3\sqrt{2}} \epsilon \tan\beta \left[\frac{h^i_d}{\overline{\overline{h^i_d}}}\ \left(\delta^d_{ij}\right)_{LL} + \frac{h^j_d}{\overline{\overline{h^i_d}}}\ \left(\delta^d_{ij}\right)_{RR} \right] \left(\tan\beta\ C^d_a - C^{u\star}_a \right) \overline{d^i_R}\ d^j_L\ H_a
\end{aligned}
$$

where $C^d_a \equiv \{-\sin\alpha,\ \cos\alpha, i\sin\beta,\ -i\cos\beta\}$ and $C^u_a \equiv \{\cos\alpha,\ \sin\alpha, i\cos\beta, i\sin\beta\}$ in the basis $H_a \equiv \{h, H, A, G\}$ if the CP violation effects in the Higgs sector are neglected (which can be quite sizeable [4] and add additional CP-odd phases [5] to Higgs-quark interactions). Similar structures also hold for the up sector. The interactions contained in (3) have important implications for both FCNC transitions and Higgs decay modes. The FCNC processes are contributed by both the sparticle loops (*e.g.* the gluino-squark box diagram for K^0–$\overline{K^0}$ mixing) and Higgs exchange amplitudes. The constraints on various mass insertions can be satisfied by a partial cancellation between these two contributions if M_{SUSY} is close to the weak scale. (This parameter domain needs a global analysis of FCNC constraints to determine for what ranges of SUSY parameters the bounds on mass insertions are relaxed.) On the other hand, if M_{SUSY} is high then the only surviving SUSY contribution is the Higgs exchange. The main question to be answered is: Is it possible to saturate FCNC bounds with $O(1)$ mass insertions? Concerning this point, consider $B_d \to \mu^+\mu^-$ decay, which has a rather small SM background, for $M_{SUSY} \gg m_t$. Using the explicit expressions of Yukawa couplings (1) in (3) one finds that the Higgs exchange contribution to this decay gets totally suppressed with $O(1)$ mass insertions for $\tan\beta \simeq (\tan\beta)_{max}$ and $\phi_\mu + \phi_g \rightsquigarrow \pi$. Therefore, in this

parameter domain, though the flavor-changing Higgs decay channels are sealed up the decays into similar quarks are highly enhanced. For instance, $\Gamma(h \to \overline{d}d)/\Gamma(h \to \overline{b}b) \simeq (\mathrm{Re}\,[h_d/h_b])^2$ which is $O(1)$ when $h_d \sim h_b$ as is the case with SUSY flavor violation. Such enhancements in light quark Yukawas induce significant reductions in $\overline{b}b$ branching fraction — which is a very important signal for hadron colliders to determine the non-SM structure of the Higgs boson ($h \to \overline{b}b$ has $\sim 90\%$ branching fraction in the SM). If FCNC constraints are saturated without a strong suppression of the flavor-changing Higgs couplings (which requires M_{SUSY} to be close to the weak scale) then Higgs decays into dissimilar quarks get significantly enhanced. For instance, $h \to \overline{b}s + \overline{s}b$ can be comparable to $h \to \overline{b}b$. (See [6] for a diagrammatic analysis of $\to \overline{b}s + \overline{s}b$ decay.) In conclusion, as fully detailed in [3], SUSY flavor and CP violation sources significantly modify Higgs–quark interactions whereby inducing potentially large effects that can be discovered at hadron colliders as well as meson factories.

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